Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7-11 July 2008
Session number 3

Remote sensing of changes in carbonate production on coral reefs: The Florida Keys

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Abstract. Using satellite remote sensing, it is possible to scale-up *in situ* carbonate production observations on coral reefs from habitat (10^{-1}-10^{0} km^2) to regional (10^{3}-10^{4} km^2) scales. Using a time series of Landsats 5 TM and 7 ETM+ spanning 18 years from 1984-2002 with 30 m spatial resolution, it is possible to quantify changes in the spatial extent of reef habitats in the Florida Keys. This study focused on the shallow (<6 m) backreefs, reef flats, and forereefs along the length of the Florida Keys. Twenty-eight georectified images were subjected to atmospheric and water-column corrections, then calibrated for change detection analyses. Published values for production were applied additively to estimate overall changes in production. A reduction in cover of coral habitat of >50% is observed both *in situ* and by satellite data over this time, and is reflected in an estimated decline in production of ~39%. Similar approaches could be applied over other areas with good temporal availability of remote sensing imagery validated by *in situ* observations. Using remote sensing as a tool for scaling-up *in situ* measurements of production has potential applications for modeling synoptic scale environmental impacts, such as the broad reaching effects from ocean acidification.

Key words: remote sensing, ocean acidification, carbonate, Landsat, change detection.

Introduction

Mounting evidence suggests that global climate change, including ocean acidification, will have negative impacts on marine calcifiers, especially coral reef ecosystems (Smith and Buddemeier 1992; Kleypas et al. 2001; Walther et al. 2002; Hughes et al. 2003; Kleypas et al. 2006; Kuffner et al. 2007). Increases in atmospheric and oceanic partial pressure of carbon dioxide (pCO_2) drive changes in the carbonate chemistry of surface ocean waters, decreasing pH and carbonate ion concentration [CO_3^{-2}] (Zeebe and Wolf-Gladrow 2003; Feely et al. 2004). The drop in pH and [CO_3^{-2}] decrease the aragonite ($CaCO_3$) saturation state, making it more difficult for corals to secrete their aragonite skeletons (Gattuso et al. 1998; Kleypas et al. 1999; Gattuso and Buddemeier 2000; Fine and Tchernov 2007).

However, some *in situ* research has indicated that on the scale of reefs or reef biotopes, the net production of carbonate can vary widely (Yates and Halley 2006). Therefore, neither simple geochemical extrapolations, nor single reef-scale metabolic estimates alone can be reliably used to monitor the impact of environmental changes such as ocean acidification on reef processes across time without accounting for changes in reef communities and habitats.

The net metabolism of a given reef zone or biotope can be accounted for by the balance of productivity, or gross photosynthetic carbon fixation (*P*), and respiration (*R*), or their difference, the measure of excess production (*E*) (Kinsey 1985). In addition to carbon metabolism, the amount of carbonate mineral precipitation (*G*) can also be an estimate of reef "health" (Kinsey 1985).

Kinsey (1983) established a linear range of reef metabolic end members, with *P* ranging from 1 g C m^{-2} d^{-1} (100% sand and rubble) to 20 g C m^{-2} d^{-1} (100% coral-algal hard substrate). Calcification also had a linear relationship to the same end members with *G* ranging (respectively) from 0.5 g $CaCO_3$ m^{-2} d^{-1} to 10 g $CaCO_3$ m^{-2} d^{-1} (Kinsey 1983). These metabolic parameters are assumed to have additive properties when scaling-up with remote sensing (Atkinson and Grigg 1984; Andréfouët and Payri 2001).

Despite the general agreement on reefs as sources of CO_2, there is evidence that certain reefs, or parts of reefs, are sinks for atmospheric CO_2 (Kayanne et al. 1995; Ikeda et al. 1997; Yates and Halley 2006). Additionally, recent direct measurements on Moloka'i (Hawai'i, USA) indicate that a reef may operate simultaneously as both a source and a sink in patchy patterns related to biotope spatial distribution (Yates and Halley 2006). This habitat-scale spatial variability of CO_2 production across reefs reflects similar patchiness in carbonate precipitation.

Here we: (1) demonstrate the potential of a time series of Landsat imagery to estimate changes in reef carbonate production over large areas, and (2) report that Landsat based estimates indicate a ~39% reduction in carbonate production across the scope of the Florida Keys since 1984. These results provide important estimates of carbonate precipitation and ecosystem functioning over spatial and time scales that are relevant to ecosystem based management and models of regional responses to ocean acidification.

Material and Methods

Location

The Florida Keys are a chain of low islands extending nearly 400 km from the southeastern tip of Florida to the south and west forming the seaward margin of Florida Bay. In the Keys, the basic zonation proceeds seaward from the islands with a broad, shallow seagrass flat, followed by Hawk Channel with seagrass and patch reefs, then shallowing again to the barrier reef complex ~5 km offshore. The Florida Keys have an unfortunately well documented record of decline in reef health in recent decades (Dustan et al. 2001; Gardner et al. 2003; CREMP 2005; Palandro et al. 2008). This study focused on several shallow portions of the barrier reef complex ≤6 m deep, specifically at Carysfort Reef, Grecian Rocks, Molasses Reef, Looe Key Reef, Western Sambo, and Sand Key Reef (Fig. 1). These sites are representative of shallow barrier reefs of the Florida Keys. They were selected in part because each is a Sanctuary Preservation Area within the Florida Keys National Marine Sanctuary, and in part because these sites have been monitored annually by the Coral Reef Evaluation and Monitoring Program (CREMP) since 1996.

Image Classification, Validation, and Interpretation

Eight Landsat 5 TM and four Landsat 7 ETM+ images were used for this study. Both satellite sensors are equipped with three discrete visible spectral bands useful for this study, specifically the blue (450 nm–520 nm), green (520 nm–600 nm) and red (630 nm–690 nm) bands. This study used images acquired in 1984, 1988, 1992, 1996, 2000, and 2002 during the spring season (March–May). Two Landsat scenes were required to cover the Florida Keys Reef Tract (path/row 15/43 and 16/43). The images were resampled at 30 m spatial resolution, georectified, and transformed to at sensor radiance (L) using calibration coefficients provided with each file. Atmospheric and water-column corrections were applied to each image, and images were calibrated for change detection by an empirical line calibration as detailed in Palandro et al. (2008). Detailed image classifications for these sites are also available in Palandro et al (2008).

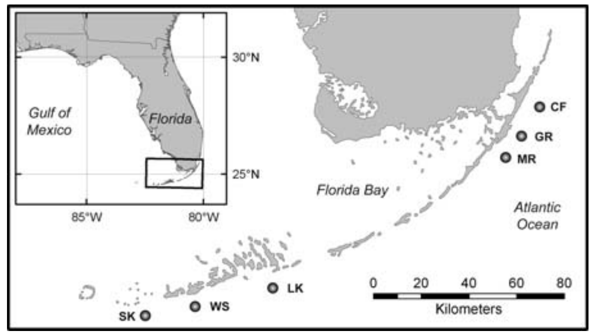

Figure 1. Location map of study sites in the Florida Keys. CF = Carysfort Reef; GR = Grecian Rocks; MR = Molasses Reef; LK = Looe Key Reef; WS = Western Sambo; SK = Sand Key Reef.

From *in situ* observation, four benthic biotopes (i.e., classes) were determined: sand, sparse live substrate, dense live substrate, and coral habitat. Dense live substrate, as measured on Florida patch reefs by Brock et al., (2006), consisted of an average of ~7% live hermatypic coral cover, ~27% macroalgae (calcareous and fleshy), about 10% gorgonians, and 21% bare hardbottom. Sparse live substrate represents areas with the same components as dense live substrate, but with ≥70% bare hardbottom. The sand class is dominated by unconsolidated carbonate sands of varying thickness. The coral habitat biotope represents areas with *in situ* observations of 22% live hermatypic (scleractinian plus hydrocoral) coral cover.

Image classification is based on training pixels determined from *in situ* observations in the same period as the 2002 Landsat images. Image classification was performed using a supervised Mahalanobis Distance classifier with ENVI image software (v4.3). Additional validation of classification was performed by proxy using higher spatial resolution IKONOS imagery, and by *in situ* data compiled from published (Lang 2003; CREMP 2005) and unpublished sources in that time interval.

For this study, the transformed divergence class separability statistic indicated each class was statistically distinct with a mean TD=1.91. Unfortunately, rigorous accuracy assessment is impossible to apply to historical data that were not collected in the context of a remote sensing study with image-driven sampling protocols. In this study, accuracy assessment of the classification for historical images was performed by generalized comparison to CREMP data.

Carbonate Parameters and Scaling

This project takes advantage of values for reef carbonate production recently reported by Brock et al. (2006) for similar biotopes, but over a smaller area of the North Florida Reef Tract (Tab. 1). The values for *G* were measured with a unique *in situ* mesocosm, the Submersible Habitat for Analyzing Reef Quality (SHARQ) that is operated by the U.S. Geological Survey (Yates and Halley 2003). Brock et al. (2006) presented values for *P*, *R*, *P/R*, *E*, and *G* for three reef biotopes common to our sites: sand, dense live substrate, and sparse live substrate. For this current study, we adopted those biotope definitions and carbonate production values. The coral habitat class value for *G* is calculated here as a linear mix of calcification end members (Kinsey 1983) representing 22% live coral cover (Tab. 1). With no *in situ* SHARQ data available for a class with 22% live coral cover, the Kinsey (1983) end members for *G* offer a suitable basis for interpolation.

Table 1. Values used for estimation of carbonate production. * = directly from Brock et al. (2006).

Class	***G*** **($g\ CaCO_3\ m^{-2}\ d^{-1}$)**
Sand*	0.11
Sparse Live Substrate*	-0.04
Dense Live Substrate*	1.29
Coral Habitat	2.64

Carbonate precipitation on coral reefs is assumed to be an additive process such that the whole is equal to the sum of the parts (Atkinson and Grigg 1984; Hatcher 1997). For example, the contribution of the coral habitat class to the carbonate production (*G*) for the whole of a given reef complex is a function of the relative fractional area (m^2). The total carbonate production for a reef area depends on the sum of the production of the included biotopes (sand, dense live substrate, sparse live substrate, coral habitat). The measured value for *G* ($g\ CaCO_3\ m^{-2}\ d^{-1}$) for each biotope (Tab. 1) is multiplied by the fractional area covered by that biotope ($F_{biotope}$). It follows as Eqn. 1:

$$G_{reef} = (F_{sand} \times G_{sand}) + (F_{dense\ live} \times G_{dense\ live}) + (F_{sparse\ live} \times G_{sparse\ live}) + (F_{coral\ habitat} \times G_{coral\ habitat}) \quad (1)$$

Two values for G_{reef} were calculated at each time step. The more conservative number was generated by assuming that in 1984, areas classified as coral habitat, consisted of 22% live coral cover like they do today, thus assuming modern levels of production (*G*) as well. However, this is not likely given the known declines in percent coral cover (Gardner et al. 2003; CREMP 2005). Integration of trends from published (Dustan 1985; CREMP 2005) and unpublished data for these sites produced a simple model of hindcast percent live coral cover at each site during each time interval. The model was based a linear extension of trends from CREMP data (CREMP 2005) at each of the sites, validated where possible by comparison with observations of coral cover during the 1980's. The hindcast live coral cover values in 1984 ranged from 38%-56% which was reflected in corresponding hindcast estimates of carbonate production (G_H).

Results

Validation of the benthic biotopes demonstrated that classification of the most recent (2002) Landsat images was 86% (±2%) accurate across the six reefs in this study, similar to results over much broader regions of the North Florida Reef Tract (Moses et al. in press). Sand has a broad spectral signature, leading to the most frequent misclassification of these four biotopes, typically misclassified as sparse live substrate. However, misclassification of sand as sparse live substrate has a relatively small impact on estimates of G_{reef} compared to changes in percentage of coral habitat, due to the relatively small values of *G* in those biotopes.

The decline of coral habitat correlates significantly ($r^2 = 0.71$, N = 32) with the decline in percent live coral reported by CREMP. It is important to point out that the decline measured by the 30 m Landsat pixels is decline in the area of coral habitat (a biotope that averages 22% live cover), and is not the same as the decline in percent coral cover as detected by CREMP. However, the two measures are directly related (Palandro et al. 2003; Palandro et al. 2008).

The mean conservative change in carbonate production (ΔG) between 1984-2002 over the six reefs was -20% (±22%). Without hindcast adjustment, Sand Key Reef even appears to slightly increase *G* over the study period. The mean hindcast ΔG_H suggests a greater decline of -39% (±14%) (Fig. 2). The more realistic hindcast values ranged from ΔG_H = -15% at Sand Key Reef to ΔG_H = -57% at Western Sambo.

During the period from 1996-2002, all sites suffered a steady decrease in the coral habitat biotope. Despite this, four of the six sites actually suggest slight increases in carbonate production in the 2000 or 2002 estimates. In the case at Grecian Rocks between 1996-2002, area percent of coral habitat biotope decreased from 21.7% to 14.0%, yet carbonate production increased from 1.13 to 1.20 $g\ CaCO_3\ m^{-2}\ d^{-1}$.

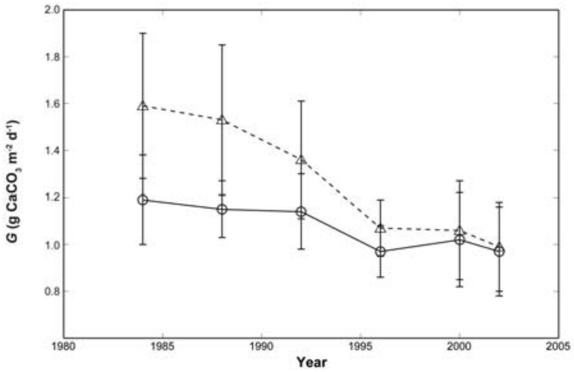

Figure 2. Average satellite estimated decline in carbonate production in the Florida Keys. Solid line with circles represents estimations based on a consistent 22% live cover (G). Dashed line with triangles represents estimates based on hindcast live coral cover (G_H).

Discussion

Work presented here suggests substantial declines in carbonate production on reefs in the Florida Keys. The roughly 40% decline in carbonate production over about two decades, an average rate of decrease of ~2% per year, implies a substantial limitation from broad reaching factors on reef accumulation in the Florida Keys.

The observed increases in G estimated for 2000 and 2002 for some sites are likely an ecological recovery in response to the 1998 bleaching event. The 1998 bleaching event reduced the actual percent live coral cover (CREMP 2005), transforming coral habitat area to sparse live substrate. Subsequent recovery of the sparse live substrate to dense live substrate increased the carbonate production, but not the area coverage of coral habitat, which continued to decline. Unfortunately, trends of live hermatypic coral cover on Florida reefs continue to suffer under substantial stressors (Maliao et al. 2008), making recovery of dense live substrate to coral habitat seem unlikely.

These results do not specifically confirm direct influence of ocean acidification on carbonate production and reef accretion in the study area. However, the results describe the magnitude and geographic scope of decline in carbonate mineral precipitation in the Florida Keys, which likely stems from a combination of antagonistic environmental factors operating across a range of scales (Gardner et al. 2003; CREMP 2005).

Models like this have the potential to be accurately applied over regions with good *in situ* habitat cover data as well as carbonate production observations. The additive model reported here does not account for complexities such as sea surface temperature or water retention time. However, improved estimates can be made by incorporating more environmental data that could influence the calculations of G. Inclusion of such components would result in a gradient of carbonate production values in each model grid cell (i.e., Landsat pixel). This would be more realistic than the current list of discrete values for G. Additional *in situ* data collection, with systems like the SHARQ, will provide more control points for benthic community production of carbonate, especially if measurements are expanded into deeper waters of previously unsampled geographic areas.

Acknowledgements

Thanks to PHM for comments and suggestions on this project. This project was possible thanks in part to funding from NASA grants NNG04GO90G, NNX07AJ84G and NGT5-30414. Thanks to students of SCUBAnauts International of Tampa Bay for assistance in field validation.

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